EMPIRICAL DETERMINATION OF HEAT CAPACITY, TIME CONSTANT, AND SENSITIVITY OF EARTH'S CLIMATE SYSTEM, AND INVERSE CALCULATION OF TOTAL FORCING AND AEROSOL FORCING

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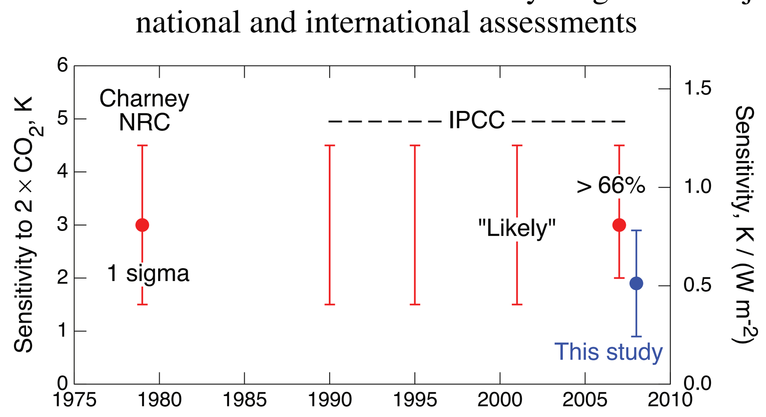
MOTIVATION

CLIMATE SENSITIVITY ESTIMATES THROUGH THE AGES

Estimates of central value and uncertainty range from major national and international assessments



IMPLICATIONS OF UNCERTAINTY IN CLIMATE SENSITIVITY

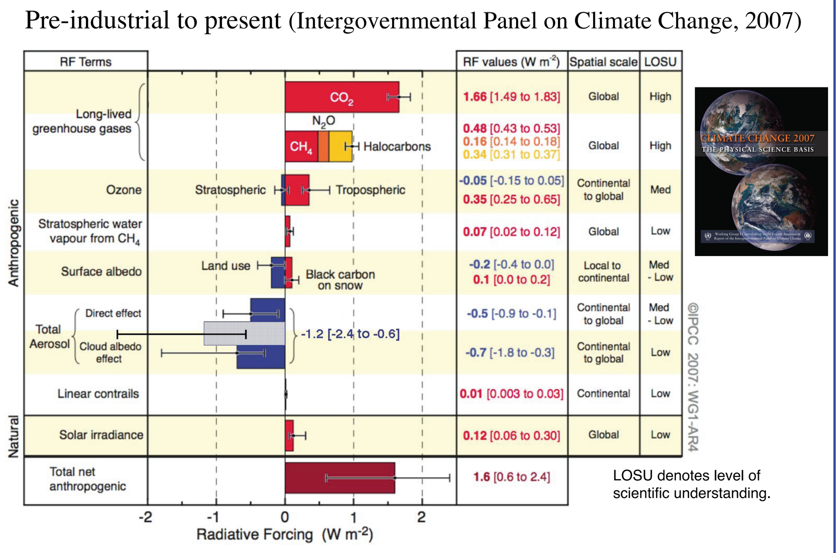
Uncertainty in climate sensitivity translates directly into . . .

- Uncertainty in the amount of ***incremental atmospheric*** $\mathbf{CO_2}$ that would result in a given increase in global mean surface temperature.
- Uncertainty in the amount of ***fossil fuel carbon*** that can be combusted consonant with a given climate effect.

At present this uncertainty is more than a factor of 2.

GLOBAL-MEAN RADIATIVE FORCINGS (RF)

Pre-industrial to present (Intergovernmental Panel on Climate Change, 2007)

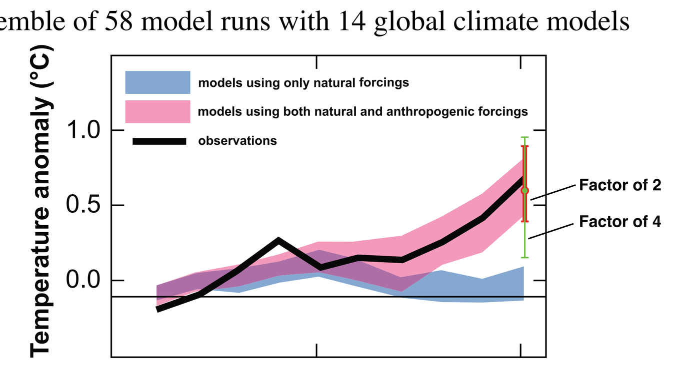


Uncertainty in aerosol forcing dominates uncertainty in total forcing.

Uncertainty in total forcing limits climate model evaluation.

TOO ROSY A PICTURE?

Ensemble of 58 model runs with 14 global climate models



Schwartz, Charlson & Rodhe, Nature Reports – Climate Change, 2007, modified from IPCC, 2007

"Models can … simulate many observed aspects of climate change over the instrumental record. One example is that the ***global temperature trend over the past century … can be modelled with high skill when both human and natural factors that influence climate are included***.

IPCC AR4, 2007

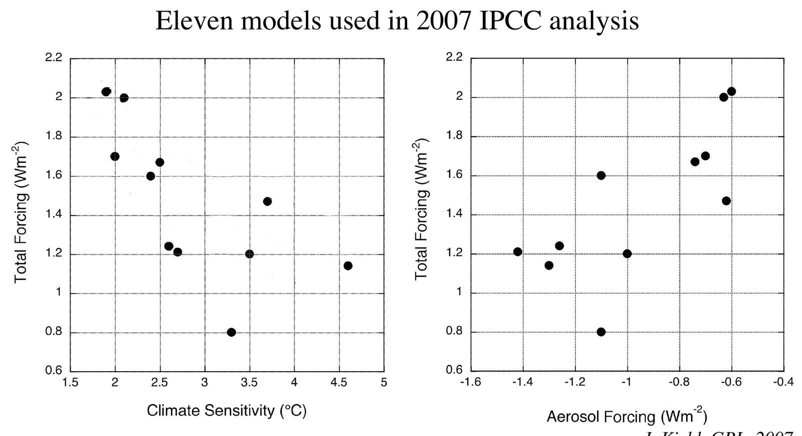
Uncertainty in modeled temperature increase – less than a factor of 2, red – is ***well less than uncertainty in forcing*** – a factor of 4, green.

The models ***did not span the full range of the uncertainty*** and/or . . .

The forcings used in the model runs were ***anticorrelated with the sensitivities of the models***.

CORRELATION OF SENSITIVITY, TOTAL FORCING, AND AEROSOL FORCING IN CLIMATE MODELS

Eleven models used in 2007 IPCC analysis



J. Kiehl, GRL, 2007

Climate models with higher sensitivity have lower total forcing.

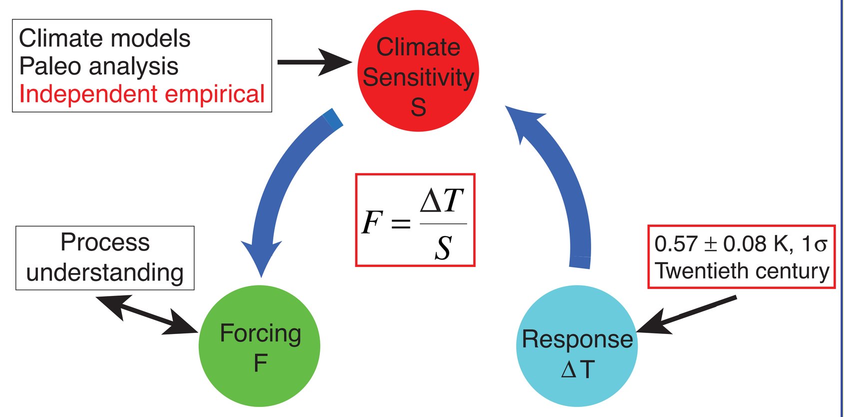
Total forcing increases with decreasing (negative) aerosol forcing.

These models cannot all be correct.

APPROACH

INVERSE CALCULATION OF CLIMATE FORCING

Requires knowledge of climate sensitivity and temperature change



$$F = \frac{\Delta T}{S}$$

Bound estimates on forcing.

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Heat capacity, time constant, and sensitivity of Earth's climate system

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[1] The equilibrium sensitivity of Earth's climate is determined as the quotient of the relaxation time constant of the system and the pertinent global heat capacity. The heat capacity of the global ocean, obtained from regression of ocean heat content versus global mean surface temperature, GMST, is 14 ± 6 W a m^{-2} K^{-1}, equivalent to 110 m of ocean water; other sinks raise the effective planetary heat capacity to 17 ± 7 W a m^{-2} K^{-1} (all uncertainties are 1-sigma estimates). The time constant pertinent to changes in GMST is determined from autocorrelation of that quantity over 1880–2004 to be 5 ± 1 a. The resultant equilibrium climate sensitivity, 0.30 ± 0.14 K/(W m^{-2}), corresponds to an equilibrium temperature increase for doubled CO_2 of 1.1 ± 0.5 K. The short time constant implies that GMST is in near equilibrium with applied forcings and hence that net climate forcing over the twentieth century can be obtained from the observed temperature increase over this period, 0.57 ± 0.08 K, as 1.9 ± 0.9 W m^{-2}. For this forcing considered the sum of radiative forcing by incremental greenhouse gases, 2.2 ± 0.3 W m^{-2}, and other forcings, other forcing agents, mainly incremental tropospheric aerosols, are inferred to have exerted only a slight forcing over the twentieth century of −0.3 ± 1.0 W m^{-2}.

ENERGY BALANCE MODEL OF EARTH'S CLIMATE SYSTEM

Global energy balance: $C\frac{dT_s}{dt} = \frac{dH}{dt} = Q - E = \gamma J - \varepsilon\sigma T_s^4$

C is heat capacity coupled to climate system on relevant time scale

T_s is global mean surface temperature H is global heat content

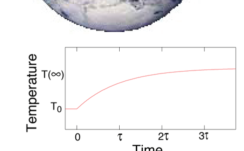
Q is absorbed solar energy E is emitted longwave flux

J is $\frac{1}{4}$ solar constant γ is planetary co-albedo

σ is Stefan-Boltzmann constant ε is effective emissivity

ENERGY BALANCE MODEL OF EARTH'S CLIMATE SYSTEM

Apply step-function forcing: $F = \Delta(Q - E)$



At "equilibrium" $\Delta T_s(\infty) = SF$

Stefan-Boltzmann sensitivity

S is equilibrium climate sensitivity $S = f\frac{T_0}{4\gamma_0 J_S}$ K / (W m^{-2})

f is feedback factor $f = \frac{1}{\left(1 - \frac{1}{4}\frac{d\ln\gamma}{d\ln T}\Big|_0 + \frac{1}{4}\frac{d\ln\varepsilon}{d\ln T}\Big|_0\right)}$

Time-dependence: $\Delta T_s(t) = SF(1 - e^{-t/\tau})$

τ is climate system time constant $\tau = CS$ or $S = \tau / C$

One equation in three unknowns!

APPROACH TO DETERMINE EARTH'S CLIMATE SENSITIVITY

Empirically determine heat capacity C and time constant τ of Earth's climate system from observations over the instrumental period.

Evaluate sensitivity as $S = \tau/C$.

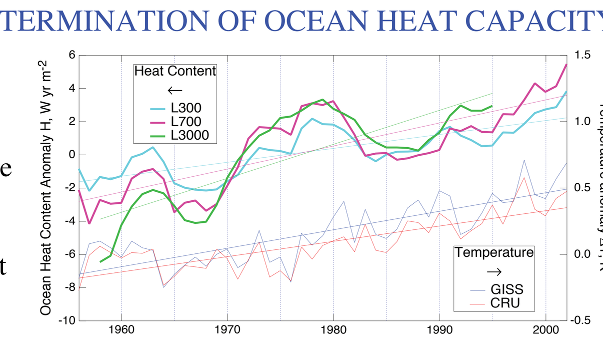
DETERMINATION OF SENSITIVITY AND FORCING

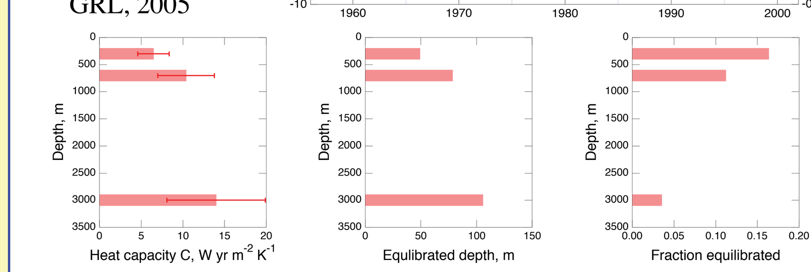
EMPIRICAL DETERMINATION OF OCEAN HEAT CAPACITY

$$C = \frac{dH/dt}{dT_s/dt}$$

Surface temperature T_s: GISS, CRU

Ocean heat content H: Levitus *et al.*, GRL, 2005





- ~50% of heat capacity is between surface and 300 m.
- Other heat sinks raise global heat capacity to 17 ± 7 W yr m^{-2} K^{-1}.

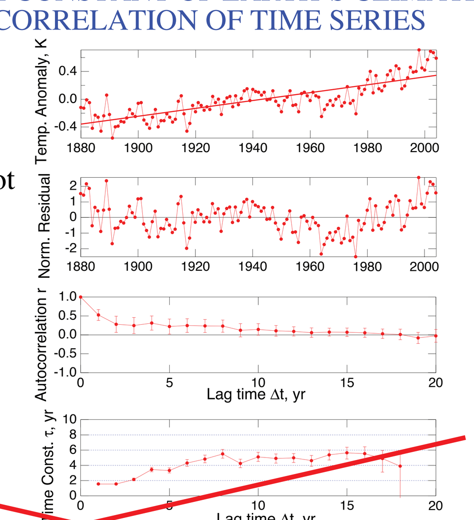
DETERMINATION OF TIME CONSTANT OF EARTH'S CLIMATE SYSTEM FROM AUTOCORRELATION OF TIME SERIES

Annual global mean surface temperature anomaly T_s

Remove long term trend; plot the residuals

Calculate autocorrelogram (& standard deviations; Bartlett, 1948)

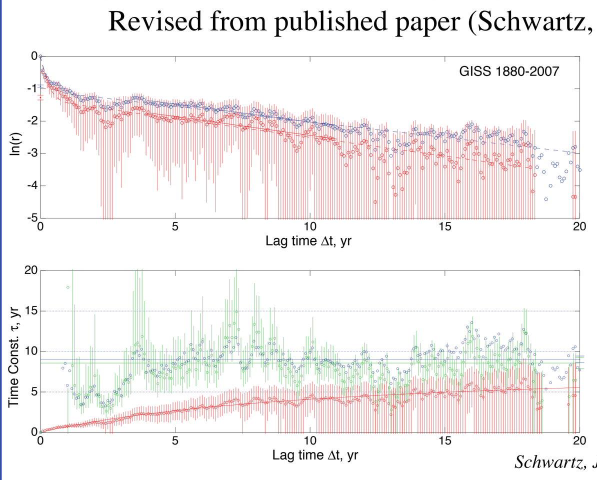
~~Calculate time constant τ for relaxation of system to perturbation (Leith, 1973) $\tau(\Delta T) = -\Delta T / \ln r(\Delta T)$~~



- ~~This is the ***e-folding time constant*** for relaxation of global mean surface temperature to perturbations on the decadal scale.~~
- ~~On decadal scale time constant ***asymptotes to 5 ± 1 yr***.~~

REVISED DETERMINATION OF TIME CONSTANT

Revised from published paper (Schwartz, *JGR*, 2007)



Semilogarithmic plot yields time constant as slope of monthly data:

$$\tau = -\frac{1}{d\ln r(\Delta t) / d\Delta t}$$

← New estimate
← Old estimate

Schwartz, JGR, in review

Climate system time constant τ = 8.5 ± 2.5 yr (vice 5 ± 1 yr).

Revision takes into account rapid initial decorrelation on time scale of 0.4 years, which leads to slow asymptotic approach to final value.

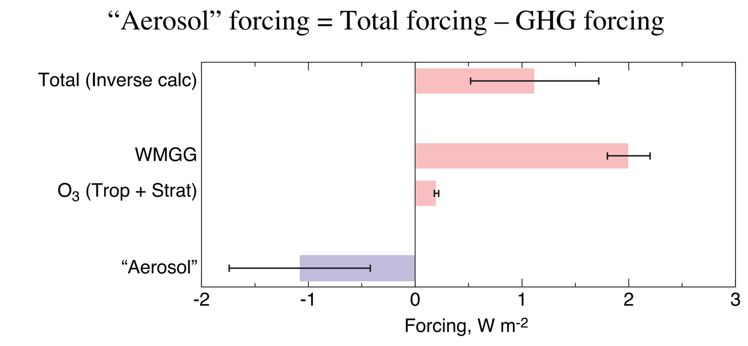
Blue includes estimated correction for short duration of time series.

EVALUATION OF SENSITIVITY AND FORCINGS

Quantity	Unit	Value	1 σ
Effective global heat capacity C	W yr m^{-2} K^{-1}	**17**	**7**
Effective climate system time constant τ	yr	**8.5**	**2.5**
Equilibrium climate sensitivity $S = \tau / C$	K/(W m^{-2})	**0.51**	**0.26**
Equilibrium temperature increase for 2 × CO_2, $\Delta T_{2\times}$	K	**1.9**	**1.0**
Total forcing over the 20th century, $F_{20} = \Delta T_{20} / S$	W m^{-2}	**1.1**	**0.6**
Forcing in 20th century other than GHGs (*mainly aerosols*), $F_{20}^{other} = F_{20} - F_{20}^{ghg}$	W m^{-2}	**-1.1**	**0.7**
Lag in temperature change, ΔT_{lag}	K	**0.05**	

INVERSE CALCULATION OF "AEROSOL" FORCING OVER TWENTIETH CENTURY

"Aerosol" forcing = Total forcing – GHG forcing



Total forcing is dominated by greenhouse gas forcing.

"Aerosol" forcing, calculated as residual, is small, with large uncertainty.

"Aerosol" forcing is presumably dominated by aerosols.

Accuracy of "aerosol" forcing depends on accuracy of total forcing.

CONCLUSIONS

- ***Climate system time constant*** **8.5 ± 2.5 yr** is somewhat greater than given by Schwartz (2007) 5 ± 1 yr.
- This short time constant implies ***little heating "in the pipeline,"* 0.05 K**.
- ***Climate sensitivity*** **0.51 ± 0.26 K/(W m^{-2})**, (**$\Delta T_{2\times}$ = 1.9 ± 1.0 K**) is somewhat greater than given by Schwartz (2007) 0.30 ± 0.14 K/(W m^{-2}), ($\Delta T_{2\times}$ = 1.1 ± 0.5 K), but still lower than most current estimates.
- ***Total forcing over the twentieth century*** from inverse calculation is **1.1 ± 0.6 W m^{-2}**.
- ***"Aerosol" forcing over the twentieth century***, calculated as residual, is **-1.1 ± 0.7 W m^{-2}**.
- This aerosol forcing is ***at the low end of most present forward calculations***.

QUESTIONS AND ANSWERS

? Would you bet the ranch on this analysis?

Of course not.

? Does this sort of analysis put the GCMs out of business?

Of course not. GCMs are essential to give a differentiated picture of the consequences of any perturbation to Earth's radiation budget. This global analysis gives only a single number for climate sensitivity. But hopefully it can usefully constrain climate models.

? Why was there such an uproar over your paper?

Probably because it yielded such a low climate sensitivity, and many people were concerned that this result would undermine the view that the science is solved, and weaken the argument that control over carbon dioxide is necessary.

? Do you think this revision will diminish the concern over your paper?

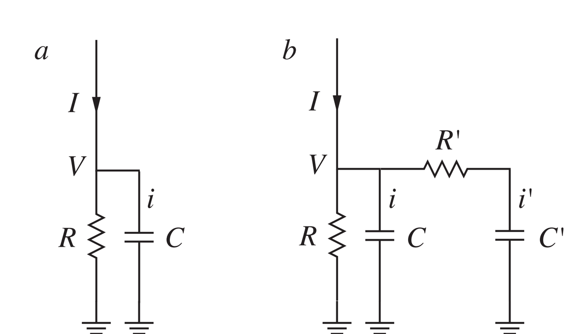
Perhaps somewhat, but there remain many concerns: multiple time constants of the climate system, for example. I expect discussions to continue.

? Your paper shows that little of the ocean is coupled to the climate system; only about 150 meters. Doesn't heat flow to the deep ocean diminish the sensitivity you determine?

The effective heat capacity that I determine is based on the entire heat flow into the ocean, as determined by the Levitus et al. (2005) compilation, so there is no additional heat flow that is unaccounted for.

? But what about the rest of the ocean? When that heats up to equilibrium wouldn't there be further heating, for constant forcing, because this sink is no longer available?

No, as the electrical circuit analogy below should help make clear.



Here the resistance R is the unknown climate sensitivity, which determines the change in voltage δV (delta temperature) for a given incremental current δI (forcing)? The sensitivity of circuit a is the same as that in circuit b which has an additional resistor and capacitor R' and C'.

? What other insights do you get from the electrical circuit analogy?

First, determining the climate sensitivity as the time constant divided by the heat capacity is analogous to determining R from the time constant τ = RC divided by the capacitance C. Also the time constant of the second circuit can be estimated as the current (heat) flow into the deep ocean, (capacitor C') as the quotient of the charge Q' that the capacitance will hold when charged to the voltage V, i.e., Q' = VC' , divided by the current i'; that is, τ' = Q'/i' = VC'/i'. Based on the heat capacity of the deep ocean (3800 m average depth) and the estimated heat flow into the deep ocean, that time constant is about 3000 years. So the systems are decoupled.